Top-quark couplings
Yukawa coupling, FCNC, W helicity

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On behalf of the ATLAS, CDF, CMS, and DØ collaborations

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Top at twenty
FNAL, 9-10 April 2015

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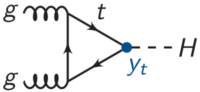

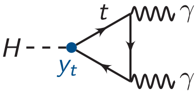

Top-quark Yukawa coupling

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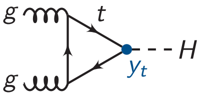
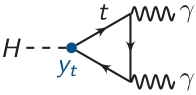
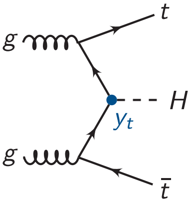
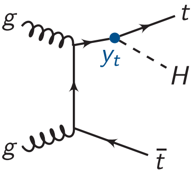
  - An indication of a special role in EWSB?
- Can be probed in H production via gluon fusion or $H \to \gamma\gamma$ decays thanks to top-quark loops
  - BSM particles can contribute to the loops
- Direct access to $|y_t|$ is provided in $t\bar{t}H$ production
  - But a challenging process: $\sigma_{t\bar{t}H} \approx 130\,\text{fb}$ at $8\,\text{TeV}$, $\sigma_{t\bar{t}H}/\sigma_{t\bar{t}} \sim 10^{-3}$



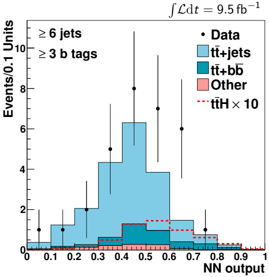






Search for $t\bar{t}H$, $H \to b\bar{b}$

- Search[1] by CDF:
  - NN analysis in $t\bar{t} \to \ell +$ jets channel
  - Obs. (exp.) upper limit: $\sigma/\sigma^{\mathrm{SM}}_{t\bar{t}H} < 20.5\ (12.6)$



[1] Phys. Rev. Lett. 109 (2012) 181802

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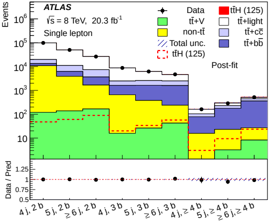
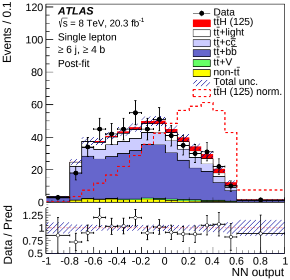
- ATLAS search[2] with MEM and NN
  - $t\bar{t} \to \ell +$ jets or $\ell\ell +$ jets
  - NNs trained in signal-enriched bins
  - In addition, classification $t\bar{t}H$ vs $t\bar{t}b\bar{b}$ with MEM
    - MEM decisions are fed into the NNs
  - Simultaneous fit of multiple jet-tag bins
    - NN responses in signal-enriched bins
    - $H_{\mathrm{T}}^{\mathrm{jet}}$ or $H_{\mathrm{T}}^{\mathrm{all}}$ in signal-depleted bins





[1] Phys. Rev. Lett. 109 (2012) 181802
[2] arXiv:1503.05066, submitted to Eur. Phys. J. C

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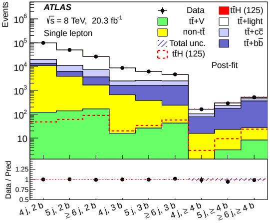
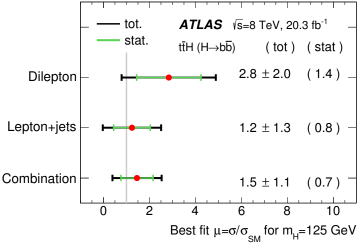
    - $H_{\mathrm{T}}^{\mathrm{jet}}$ or $H_{\mathrm{T}}^{\mathrm{all}}$ in signal-depleted bins
  - Results:
    - Signal strength $\mu = \sigma/\sigma^{\mathrm{SM}}_{t\bar{t}H} = 1.5 \pm 1.1$
    - Obs. (exp.) limit: $\mu < 3.4\ (2.2)$





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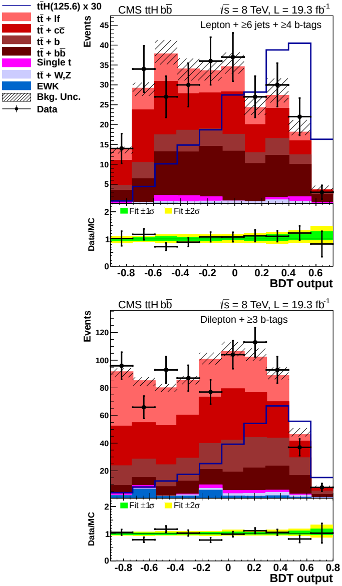
Search for $t\bar{t}H$, $H \to b\bar{b}$

- Two searches by CMS in $H \to b\bar{b}$
  - Both utilise $t\bar{t} \to \ell(\ell) + \text{jets}$ decays
  - Historically first analysis[1] exploits BDT
    - Additional BDT in some $\ell +$ jets categories to discriminate $t\bar{t}H$ vs $t\bar{t}b\bar{b}$
    - It is fed as an input to the final BDT
    - Results: $\mu = 0.7 \pm 1.9$



[1] JHEP09 (2014) 087
[2] arXiv:1502.02485, submitted to Eur. Phys. J. C

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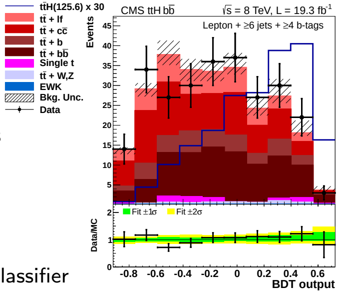
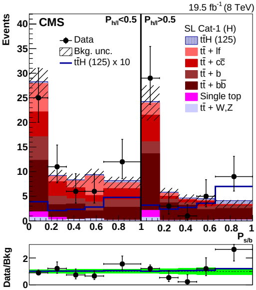
    - It is fed as an input to the final BDT
    - Results: $\mu = 0.7 \pm 1.9$
  - Second search[2] utilises MEM
    - Advanced b-tag selection using likelihood classifier
    - Discrimination $t\bar{t}H$ vs $t\bar{t}b\bar{b}$ with MEM
    - 2D fit to the two discriminators
    - Results: $\mu = 1.2^{+1.6}_{-1.5}$





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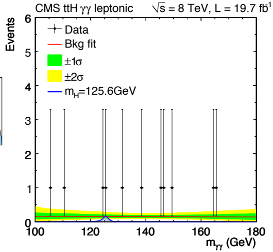
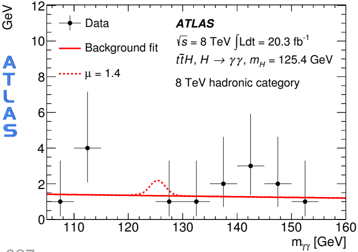
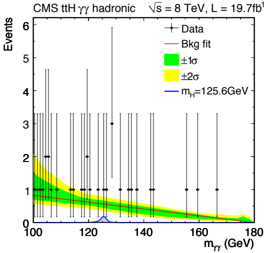
Search for $t\bar{t}H$, $H \to \gamma\gamma$

- Profit from high purity of the $H \to \gamma\gamma$ channel
- Similar approaches by CMS[1] and ATLAS[2]
  - All decays of $t\bar{t}$ system considered
  - Amount of signal and non-resonant bkg estimated from a fit to $m_{\gamma\gamma}$
  - Results (7+8 TeV):
    CMS: $\mu = 2.7^{+2.6}_{-1.8}$, ATLAS: $\mu = 1.3^{+2.6}_{-1.7}$



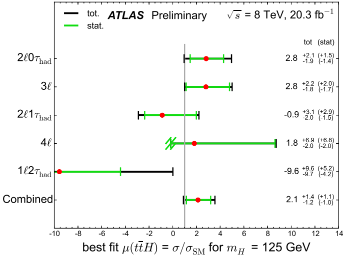




[1] JHEP09 (2014) 087
[2] Phys. Lett. B740 (2015) 222

Search for $t\bar{t}H$ in multilepton channel

- Targets $H \to WW^*$, ZZ^*, and $\tau\tau$ decays
- ATLAS search[1]:
  - Signatures: $\ell^{\pm}\ell^{\pm}$, 3ℓ, $\ell^{\pm}\ell^{\pm}\tau_{\mathrm{h}}$, 4ℓ, $\ell\tau_{\mathrm{h}}^{+}\tau_{\mathrm{h}}^{-}$
  - Counting experiment
  - Combined result: $\mu = 2.1^{+1.4}_{-1.2}$



[1] CONF-2015-006

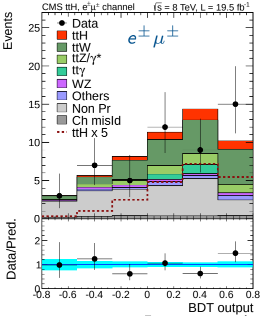
Search for $t\bar{t}H$ in multilepton channel

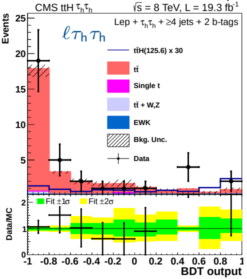
- Targets $H \to WW^*$, ZZ^*, and $\tau\tau$ decays
- ATLAS search[1]:
  - Signatures: $\ell^\pm\ell^\pm$, 3ℓ, $\ell^\pm\ell^\pm\tau_\mathrm{h}$, 4ℓ, $\ell\tau_\mathrm{h}^+\tau_\mathrm{h}^-$
  - Counting experiment
  - Combined result: $\mu = 2.1^{+1.4}_{-1.2}$
- CMS analysis[2]:
  - $\ell^\pm\ell^\pm$, 3ℓ, 4ℓ, $\ell\tau_\mathrm{h}^+\tau_\mathrm{h}^-$ channels
  - Signal extracted with a fit to # jets in 4ℓ and to BDT response elsewhere
  - Results in individual channels:

$\ell^\pm\ell^\pm$	$+5.3^{+2.1}_{-1.8}$
3ℓ	$+3.1^{+2.4}_{-2.0}$
4ℓ	$-4.7^{+5.0}_{-1.3}$
$\ell\tau_\mathrm{h}\tau_\mathrm{h}$	$-1.3^{+6.3}_{-5.5}$

Comb. with $b\bar{b}$ and $\gamma\gamma$:

$\mu = 2.8^{+1.0}_{-0.9}$

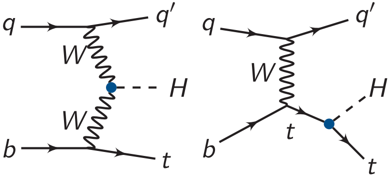




[1] CONF-2015-006
[2] JHEP09 (2014) 087

Sign of y_t: tH

- Can access sign of y_t (defined w. r. t. HWW coupling)
  - Via interference in $H \to \gamma\gamma$ loop
    - $\mathcal{B}^{y_t=-1}_{H\to\gamma\gamma} = 2.4 \times \mathcal{B}^{\text{SM}}_{H\to\gamma\gamma}$
  - At tree level in tHq production
    - $y_t = -1$ leads to $\times 13$ increase in σ



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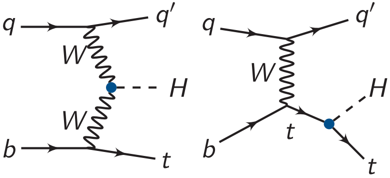

- CMS searched[1] for tHq with $y_t = -1$
  - Upper limits ($\times\sigma^{y_t=-1}_{tHq}$):

19.7 fb^{-1} (8 TeV)

H decay	$\gamma\gamma$	$b\bar{b}$	$WW/\tau_\ell\tau_\ell$
Observed	4.1	7.6	6.7
Expected	4.1	5.2	5.0

[1] CMS PAS HIG-14-001, HIG-14-015, HIG-14-026

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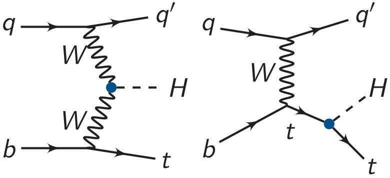

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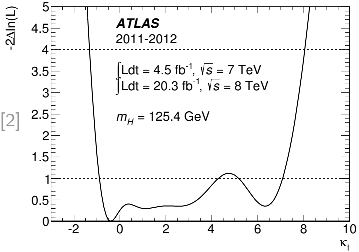
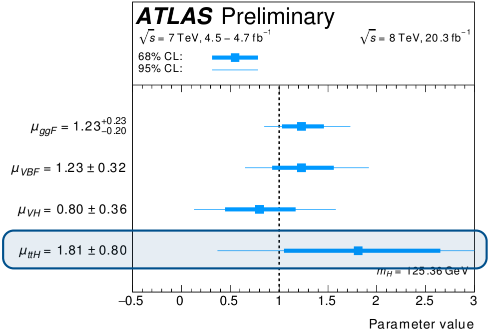
- ATLAS included tH in $t\bar{t}H(\gamma\gamma)$ search[2]
  - Derived constraints on $\kappa_t = y_t/y_t^{\mathrm{SM}}$
  - Driven in part by $\mathcal{B}(H\to\gamma\gamma)$

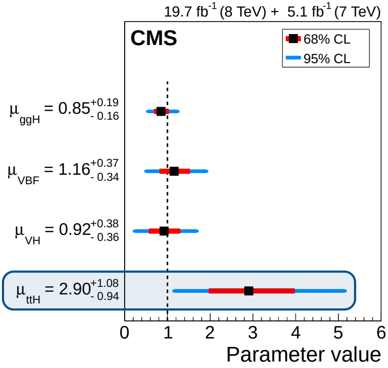


[1] CMS PAS HIG-14-001, HIG-14-015, HIG-14-026
[2] Phys. Lett. B740 (2015) 222

ATLAS and CMS combinations

- Signal strengths from global ATLAS[1] and CMS[2] fits





[1] CONF-2015-007

[2] arXiv:1412.8662, submitted to Eur. Phys. J. C

Flavour-changing neutral currents with top quarks

Flavour-changing neutral currents

- Top quark is special: it is the heaviest known particle
  - Can be sensitive to BSM interactions
- FCNC are highly suppressed in SM but can be enhanced in a number of BSM theories:

Branching ratios

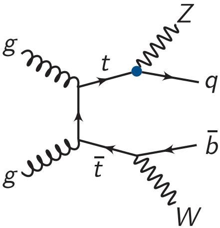
	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	–	–	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	–	–	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	–	–	8×10^{-5}	2×10^{-4}
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	–	10^{-5}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

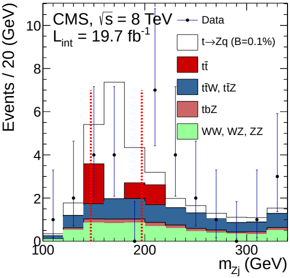
Aguilar-Saavedra, Acta Phys. Polon. B35 (2004) 2695

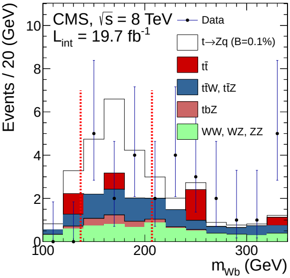
- All these vertices were probed at Tevatron and LHC, collectively
  - Because of the large number of searches, only those with most stringent limits are discussed in detail

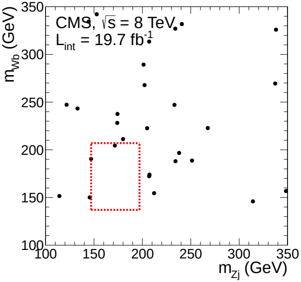
FCNC tZq

- Search[1] for $t\bar{t} \to WbZq$
  - $Z \to \ell^+\ell^-$, $W \to \ell\nu$
  - Counting experiment in 2D mass window
  - Observed limit:
    $\mathcal{B}(t \to qZ) < 5 \cdot 10^{-4}$ (7+8 TeV)





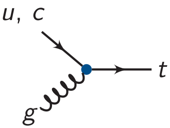




[1] Phys. Rev. Lett. 112 (2014) 171802

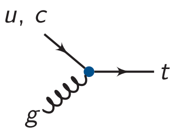
FCNC tgq

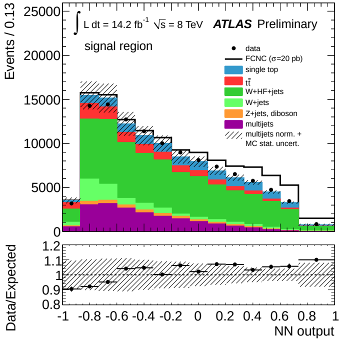
- The tgq vertex is studied in single-top production
  - $t \to gq$ decays would be too hard to identify in hadronic environment



FCNC *tgq*

- The *tgq* vertex is studied in single-top production
  - $t \to gq$ decays would be too hard to identify in hadronic environment
- Most stringent limits are from ATLAS[1]
  - Signature: $gq \to t \to b\ell\nu$
  - FCNC signal extracted with NN
    - Similar kinematics for *tgu* and *tgc*





[1] ATLAS CONF-2013-063

FCNC tgq

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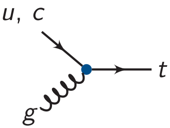
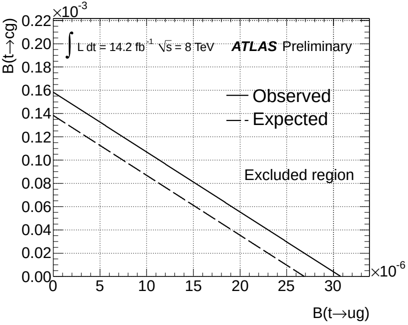


- Most stringent limits are from ATLAS[1]
  - Signature: $gq \to t \to b\ell\nu$
  - FCNC signal extracted with NN
    - Similar kinematics for tgu and tgc
  - Results (observed):

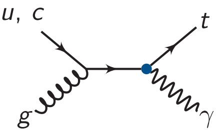
$$\mathcal{B}(t \to ug) < 3.1 \cdot 10^{-5}$$
$$\mathcal{B}(t \to cg) < 1.6 \cdot 10^{-4}$$

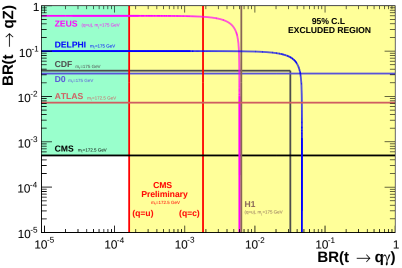


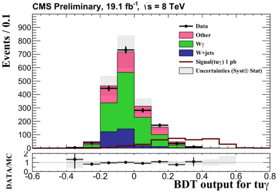
[1] ATLAS CONF-2013-063

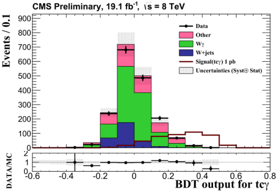
FCNC $t\gamma q$

- Studied[1] in single-top production
  - Focus on $t \to b\mu\nu$ decays only
  - Signal events identified with BDT
    - Separate BDTs trained for $t\gamma u$ and $t\gamma c$ signals
  - Observed upper limits:
    $\mathcal{B}(t \to u\gamma) < 1.6 \cdot 10^{-4}$
    $\mathcal{B}(t \to c\gamma) < 1.8 \cdot 10^{-3}$









[1] CMS PAS TOP-14-003

FCNC tHq in $t\bar{t} \to WbHc$

- Re-interpretation of a search[1] for heavy (pseudo)scalar in 2HDM
  - Multichannel counting experiment
  - Multilepton channel: $2\ell\,1\ell_3$, $3\ell\,1\ell_3$
    $\ell = e, \mu$ and $\ell_3 = e, \mu, \tau_{\mathrm{had}}$
  - Diphoton channel: $2\gamma\,\ell_3$, $2\gamma\,\ell\ell_3$
    $120 < m_{\gamma\gamma} < 130\,\mathrm{GeV}$
  - Observed limit: $\mathcal{B}(t \to cH) < 5.6 \cdot 10^{-3}$

Further categorised by number of OSSF pairs, relation to m_Z, presence of b-tagged jets, $\not{E}_{\mathrm{T}}$ $\Rightarrow$ $\sim$ 170 categories in total

19.5 fb^{-1} (8 TeV)

Ten most sensitive categories

Channel	$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	N_{b}	Obs.	Exp.	Sig.
$\gamma\gamma\ell$	(50, 100)	≥ 1	1	2.3 ± 1.2	2.88 ± 0.39
	(30, 50)	≥ 1	2	1.1 ± 0.6	2.16 ± 0.30
	(0, 30)	≥ 1	2	2.1 ± 1.1	1.76 ± 0.24
	(50, 100)	0	7	9.5 ± 4.4	2.22 ± 0.31
	$(100, \infty)$	≥ 1	0	0.5 ± 0.4	0.92 ± 0.14
	$(100, \infty)$	0	1	2.2 ± 1.0	0.94 ± 0.17
$\ell\ell\ell$ (OSSF1, below-Z)	(50, 100)	≥ 1	48	48 ± 23	9.5 ± 2.3
	(0, 50)	≥ 1	34	42 ± 11	5.9 ± 1.2
$\ell\ell\ell$ (OSSF0)	(50, 100)	≥ 1	29	26 ± 13	5.9 ± 1.3
	(0, 50)	≥ 1	29	23 ± 10	4.3 ± 1.1

Signal expectations are for $\mathcal{B}(t \to cH) = 1\%$

[1] Phys. Rev. D90 (2014) 112013

Overview of results from Tevatron and LHC

Exp.	$\sqrt{s}$	$\mathcal{B}(t \to u\gamma)$	$\mathcal{B}(t \to c\gamma)$	Reference
CDF	1.96 TeV	$3.2 \cdot 10^{-2}$		PRL 80 (1998) 2525
CMS	8 TeV	$1.6 \cdot 10^{-4}$	$1.8 \cdot 10^{-3}$	TOP-14-003
		$\mathcal{B}(t \to uZ)$	$\mathcal{B}(t \to cZ)$	
CDF	1.96 TeV	$3.7 \cdot 10^{-2}$		PRL 101 (2008) 192002
DØ	1.96 TeV	$3.2 \cdot 10^{-2}$		PLB 701 (2011) 313
ATLAS	7 TeV	$7.3 \cdot 10^{-3}$		JHEP 09 (2012) 139
CMS	7 TeV	$5.1 \cdot 10^{-3}$	$1.1 \cdot 10^{-1}$	TOP-12-021
CMS	7+8 TeV	$5 \cdot 10^{-4}$		PRL 112 (2014) 171802
		$\mathcal{B}(t \to ug)$	$\mathcal{B}(t \to cg)$	
CDF	1.96 TeV	$3.9 \cdot 10^{-4}$	$5.7 \cdot 10^{-3}$	PRL 102 (2009) 151801
DØ	1.96 TeV	$2.0 \cdot 10^{-4}$	$3.9 \cdot 10^{-3}$	PLB 693 (2010) 81
ATLAS	7 TeV	$5.7 \cdot 10^{-5}$	$2.7 \cdot 10^{-4}$	PLB 712 (2012) 351
ATLAS	8 TeV	$3.1 \cdot 10^{-5}$	$1.6 \cdot 10^{-4}$	CONF-2013-063
CMS	7 TeV	$3.6 \cdot 10^{-4}$	$3.4 \cdot 10^{-3}$	TOP-14-007
		$\mathcal{B}(t \to uH)$	$\mathcal{B}(t \to cH)$	
ATLAS	7+8 TeV	$7.9 \cdot 10^{-3}$		JHEP 06 (2014) 008
CMS	8 TeV	—	$5.6 \cdot 10^{-3}$	PRD 90 (2014) 112013
CMS	8 TeV	—	$9.3 \cdot 10^{-3}$	TOP-13-017

Overview of results from Tevatron and LHC

- Getting closer to some BSM models
  - E. g. in flavour-violating 2HDM one can expect[1] branching ratios

$$\mathcal{B}(t \to cg) \sim 10^{-4}, \quad \mathcal{B}(t \to cH) \sim 10^{-3}$$

[1] Aguilar-Saavedra, Acta Phys. Polon. B35 (2004) 2695 and refs. therein

		$\mathcal{B}(t \to ug)$	$\mathcal{B}(t \to cg)$	
CDF	1.96 TeV	$3.9 \cdot 10^{-4}$	$5.7 \cdot 10^{-3}$	PRL 102 (2009) 151801
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W-boson-helicity fractions in top-quark decays

W-boson helicity in top decays

- Top quark is special: it decays before the hadronisation
  - Its decay products thus retain information about Wtb vertex
  - Of particular interest are W-boson-helicity fractions

[1] Czarnecki, Korner, Piclum, Phys. Rev. D81 (2010) 111503

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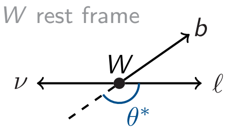
- Experimentally, the helicity fractions can be deduced from distribution in $\cos\theta^*$



$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta^*} = \frac{3}{8}F_L\,(1-\cos\theta^*)^2 + \frac{3}{4}F_0\sin^2\theta^* + \frac{3}{8}F_R\,(1+\cos\theta^*)^2\,,$$

where $F_L + F_0 + F_R = 1$

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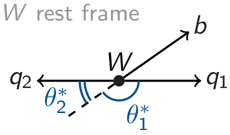

$|\cos\theta_1^*| = |\cos\theta_2^*| = |\cos\theta_{\mathrm{had}}^*|$

where $F_L + F_0 + F_R = 1$

  - For decays $t \to$ had the d-type quark is not known, but can still extract limited information from $|\cos\theta_{\mathrm{had}}^*|$

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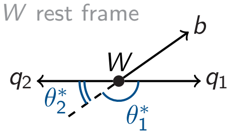

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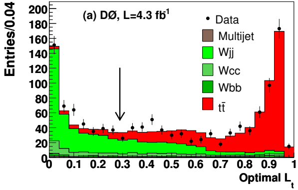
where $F_L + F_0 + F_R = 1$

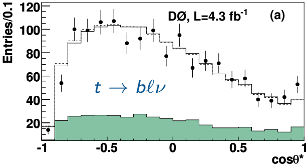
  - For decays $t \to$ had the d-type quark is not known, but can still extract limited information from $|\cos\theta^*_{\text{had}}|$
- SM values for helicity fractions[1]:
  $F_0 = 0.687(5)$, $F_L = 0.311(5)$, $F_R = 0.0017(1)$

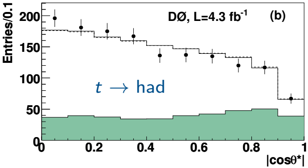
[1] Czarnecki, Korner, Piclum, Phys. Rev. D81 (2010) 111503

Tevatron results

- Long line of ever-improving measurements from Tevatron
  - Latest DØ measurement[1]:
    - $t\bar{t} \to \ell + \text{jets}$, $\ell\ell + \text{jets}$
    - Select $t\bar{t}$ events using likelihood discriminator
    - Fit both $\cos\theta^*$ and $|\cos\theta^*_{\text{had}}|$
    - Results: $F_0 = 0.67 \pm 0.10$, $F_R = 0.02 \pm 0.05$







[1] Phys. Rev. D83 (2011) 032009

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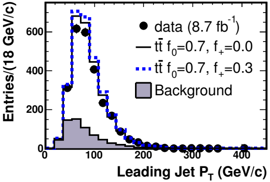
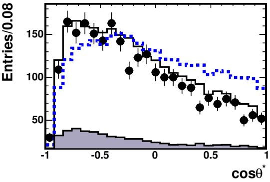
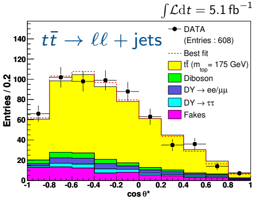
  - CDF studies (updated in 2013):
    - MEM in the $t\bar{t} \to \ell + \text{jets}$ channel[2]
    - Matrix element parameterised with $\cos\theta^*$, $F_{0,L,R}$
    - Fit to $\cos\theta^*$ in the dilepton channel[3]
    - Two channels are combined[3]. Results:
      $F_0 = 0.84 \pm 0.10$, $F_R = -0.16 \pm 0.06$

$t\bar{t} \to \ell + \text{jets}$





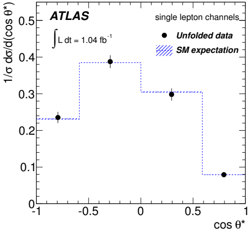


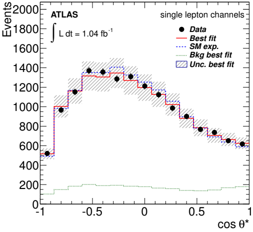
[1] Phys. Rev. D83 (2011) 032009
[2] Phys. Rev. D87 (2013) 031104
[3] Phys. Lett. B722 (2013) 48

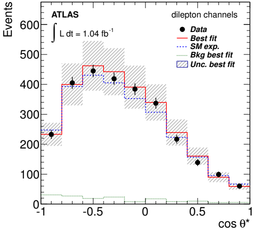
LHC results in $t\bar{t}$

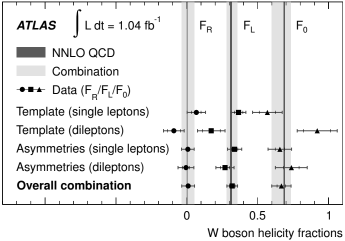
- ATLAS measurement[1] at 7 TeV:
  - $t\bar{t} \to \ell + \text{jets},\ \ell\ell + \text{jets}$
  - Fit $\cos\theta^*$ (only $t \to b\ell\nu$ decays)
  - Unfold distr. in $\cos\theta^*$ and find asymmetries $\cos\theta^* \gtrless \pm\left(\sqrt[3]{4} - 1\right)$

  Two methods in parallel
  - Combined results:
    $F_0 = 0.67 \pm 0.07,\ F_R = 0.01 \pm 0.05$









[1] JHEP 06 (2012) 088

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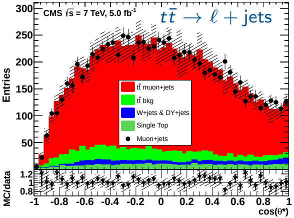
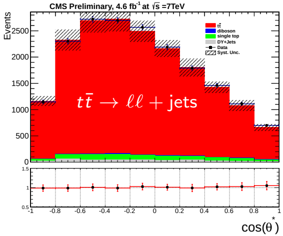


- CMS published measurements at 7[2,3] and 8 TeV[4]
  - $t\bar{t} \to \ell + \text{jets}$ (7 and 8 TeV), $\ell\ell + \text{jets}$ (7 TeV only)
  - Fit distribution in $\cos\theta^*$
    - In $\ell + \text{jets}$ at 7 TeV also utilise $|\cos\theta^*_{\text{had}}|$ but only when fixing $F_R = 0$ in the fit
  - Results:

$$\ell + \text{jets} \begin{cases} 7\,\text{TeV:} & F_0 = 0.68 \pm 0.04,\ F_R = 0.008 \pm 0.018 \\ 8\,\text{TeV:} & F_0 = 0.66 \pm 0.03,\ F_R = -0.009 \pm 0.021 \end{cases}$$

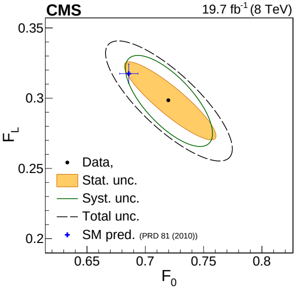
$$\ell\ell + \text{jets} \qquad F_0 = 0.70 \pm 0.08,\ F_R = 0.01 \pm 0.05$$

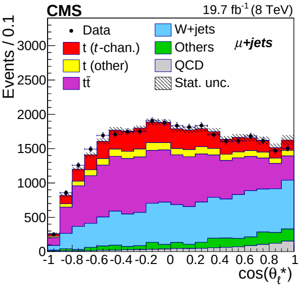


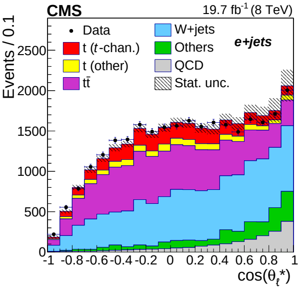
[1] JHEP 06 (2012) 088
[2] JHEP 10 (2013) 167
[3] CMS PAS TOP-12-015
[4] CMS PAS TOP-13-008

W helicity in single-top signature

- Measurement[1] in single-top signature
  - Selection optimised for t-channel single top
    - Orthogonal to the $t\bar{t}$ analyses
    - Utilise both t and $t\bar{t}$ events for the measurement
  - Fit distribution in $\cos\theta^*$
  - Results are competitive with $t\bar{t}$:
    $F_0 = 0.72 \pm 0.05,\ F_R = -0.018 \pm 0.022$

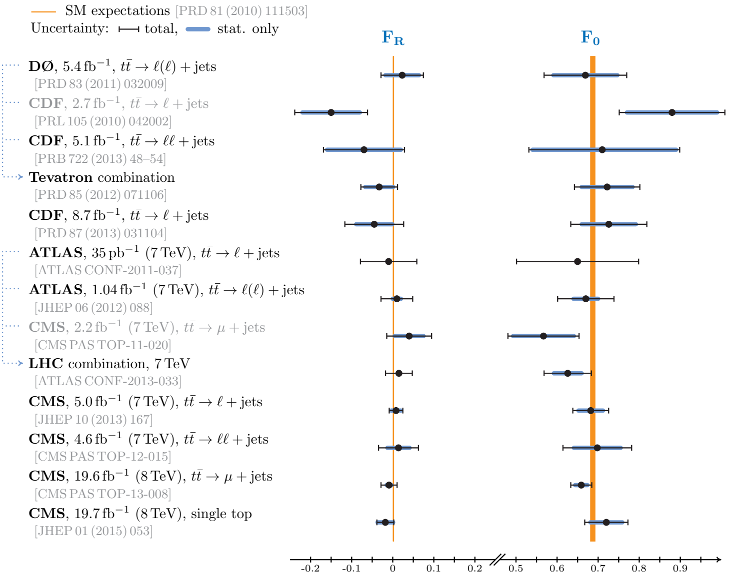






[1] JHEP 01 (2015) 053

Overview of results on W-boson helicities



Summary and conclusions

- Many excellent results delivered by Tevatron and LHC experiments
  - Cross section of $t\bar{t}H$ measured with a precision of $\sim 40\%$ ($\sim 100\%$ w. r. t. the SM expectation)
  - FCNC limits are getting close to some BSM expectations (FV 2HDM)
  - Longitudinal W-boson helicity fraction F_0 measured with a 2.3% precision. (Absolute) uncertainty on F_R has reached 0.02
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- Expect significant improvements from LHC Run II
  - Especially, in Higgs boson properties and FCNC
- LHC is recommissioning. Stay tuned!

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Thank you for your attention

Happy birthday!

Additional slides

Cross sections

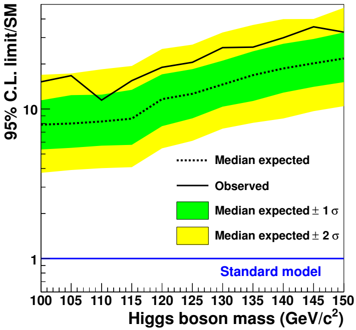
	$t\bar{t}$	$t\bar{t}H$	tHq, SM	tHq, $\kappa_t = -1$
$p\bar{p}$, 1.96 TeV	7.2 ± 0.2 pb	~ 4.9 fb†		
pp, 7 TeV	172^{+6}_{-8} pb	86^{+8}_{-11} fb		
pp, 8 TeV	246^{+9}_{-11} pb	129^{+12}_{-16} fb	18.3 ± 0.4 fb	234^{+5}_{-0} fb
pp, 14 TeV	950^{+30}_{-40} pb	610^{+70}_{-80} fb	$88.2^{+1.7}_{-0.0}$ fb	980^{+30}_{-0} fb

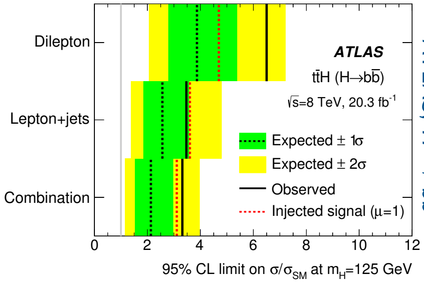
Czakon, Fiedler, Mitov, Phys. Rev. Lett. 110 (2013) 252004
Beenakker et al., Nucl. Phys. B653 (2003) 151–203
LHC Higgs cross section working group, arXiv:1101.0593, 8 TeV webpage
Farina et al., JHEP 05 (2013) 022

† $m_H = 120$ GeV; everywhere else $m_H = 125$ GeV

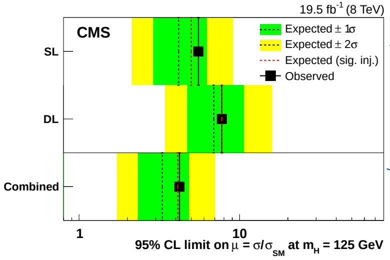
Upper limits in $t\bar{t}H$ searches

CDF, $H \to b\bar{b}$





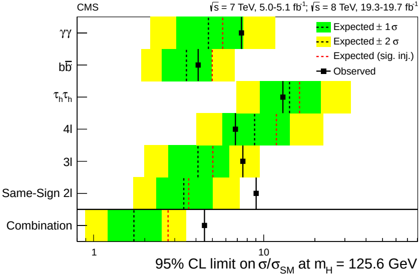
ATLAS, $H \to b\bar{b}$

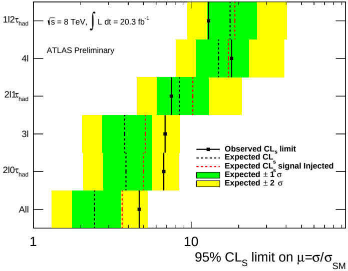


CMS, $H \to b\bar{b}$ w/ MEM

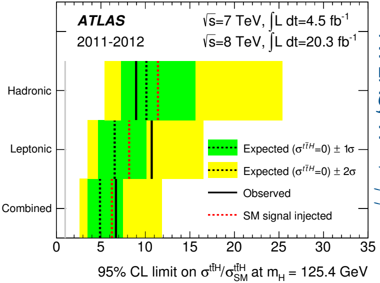
Upper limits in $t\bar{t}H$ searches

CMS, all channels



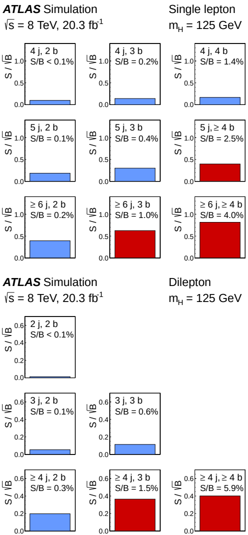


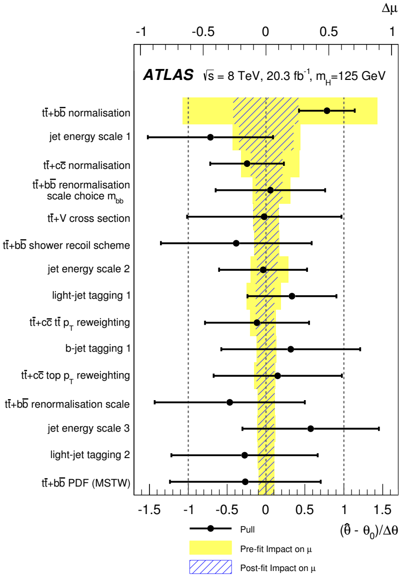
ATLAS, multilepton



ATLAS, $H \to \gamma\gamma$

ATLAS $t\bar{t}H$, $H \to b\bar{b}$ search





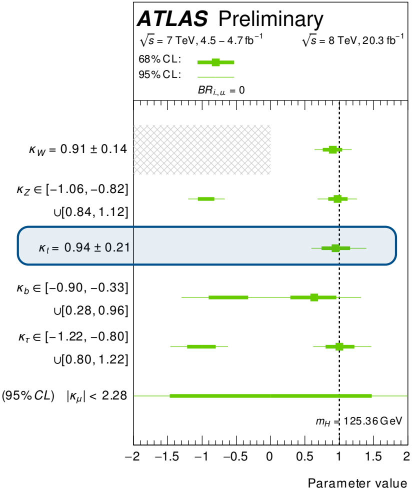
Systematics in combined CMS $t\bar{t}H$ search

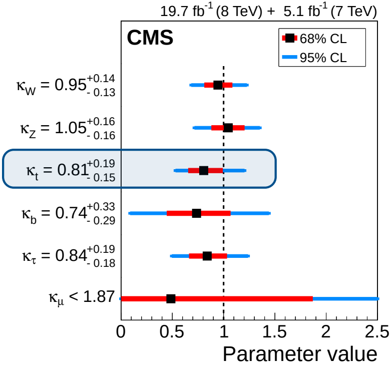
Combined search in the $b\bar{b}$, $\gamma\gamma$, and multileptonic decay channels.
Prior uncertainties, effects on rates only (i. e. not impacts on μ or limits)

Source	Rate uncertainty: Signal	Rate uncertainty: Backgrounds	Shape
Experimental			
Integrated luminosity	2.2–2.6%	2.2–2.6%	No
Jet energy scale	0.0–8.4%	0.1–11.5%	Yes
CSV b-tagging	0.9–21.7%	3.0–29.0%	Yes
Lepton reco. and ID	0.3–14.0%	1.4–14.0%	No
Lepton misidentification rate (H → leptons)	—	35.1–45.7%	Yes
Tau reco. and ID (H → hadrons)	11.3–14.3%	24.1–28.8%	Yes
Photon reco. and ID (H → photons)	1.6–3.2%	—	Yes
MC statistics	—	0.2–7.0%	Yes
Theoretical			
NLO scales and PDF	9.7–14.8%	3.4–14.7%	No
MC modeling	2.3–5.1%	0.9–16.8%	Yes
Top quark p_{T}	—	1.4–6.9%	Yes
Additional hf uncertainty (H → hadrons)	—	50%	No
H contamination (H → photons)	36.7–41.2%		No
WZ (ZZ) uncertainty (H → leptons)	—	22% (19%)	No

ATLAS and CMS combinations

No BSM particles are allowed in loop-induced higgs couplings or higgs decays

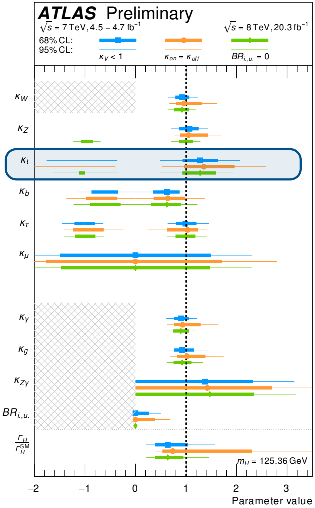


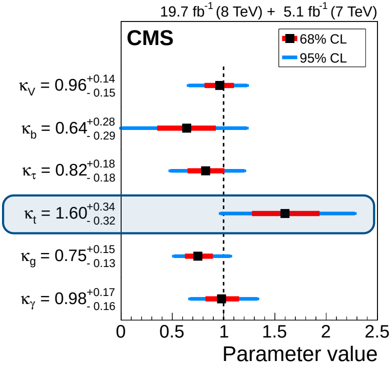


κ_t is largely constrained from $gg \to H$

ATLAS and CMS combinations

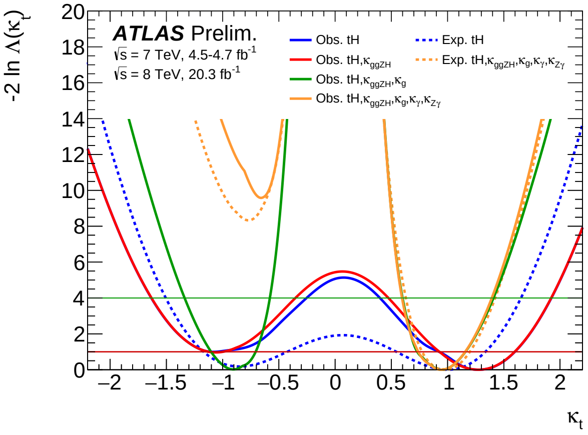
Allow loop-induced higgs couplings to depart from SM values





CMS assume $\Gamma_{\mathrm{BSM}} = 0$ and $\kappa_X > 0$.
In ATLAS plot $\Gamma_{\mathrm{BSM}} = 0$ is shown with green markers

ATLAS constraints on κ_t



- Higgs boson couples to SM particles only
- BSM contributions in loops are allowed

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Predicted FCNC branching ratios

Updated expectations (still w/o indirect contraints from LHC though):

Branching ratios: Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

Snowmass 2013 Top-quark working group report

Systematics in CMS FCNC tZq search

Prior uncertainties, effects on signal acceptance only (not impacts on limits)

Source	Uncertainty %
Renormalization/factorization scales	12
Parton distribution functions	7
$t\bar{t}$ cross section	7
Parton matching threshold	6
Lepton selection	6
Trigger efficiency	5
b-tagging	5
Top-quark mass	4
Jet energy scale	4
Missing transverse energy resolution	3
Pileup modeling	3
Total	20

Systematics in ATLAS FCNC *tgq* search

Prior uncertainties, effects on rates only (not impacts on limits)

Systematic	Signal	W+jets	W+HF+jets
Jet energy scale	$< \pm1\%$	$\pm13\%$	$\pm3\%$
Jet energy resolution	$\pm4\%$	$\pm20\%$	$\pm3\%$
b-tagging efficiency	$\pm5\%$	$\pm1\%$	$\pm1\%$
c-tagging efficiency	$< \pm1\%$	$\pm3\%$	$\pm20\%$
Mistag rate	$< \pm1\%$	$\pm26\%$	$< \pm1\%$
Muon momentum scale	$< \pm1\%$	$< \pm1\%$	$< \pm1\%$
Muon identification	$\pm1\%$	$\pm1\%$	$\pm1\%$
Electron energy scale	$< \pm1\%$	$< \pm1\%$	$< \pm1\%$
Electron identification	$\pm1\%$	$\pm1\%$	$\pm1\%$
Missing transverse momentum	$< \pm1\%$	$< \pm1\%$	$< \pm1\%$
PDF	$\pm3\%$	$\pm4\%$	$\pm8\%$
W+jets modelling	—	$< \pm1\%$	$< \pm1\%$
Cross section	—	24%	55%

Systematic	$t\bar{t}$	single-top	Z + jets
Jet energy scale	$\pm13\%$	$\pm4\%$	$\pm4\%$
Jet energy resolution	$\pm1\%$	$\pm2\%$	$\pm6\%$
b-tagging efficiency	$\pm5\%$	$\pm5\%$	$\pm4\%$
c-tagging efficiency	$< \pm1\%$	$< \pm1\%$	$\pm5\%$
Mistag rate	$< \pm1\%$	$< \pm1\%$	$\pm3\%$
Muon momentum scale	$< \pm1\%$	$< \pm1\%$	$< \pm1\%$
Muon identification	$\pm1\%$	$\pm1\%$	$\pm1\%$
Electron energy scale	$< \pm1\%$	$< \pm1\%$	$< \pm1\%$
Electron identification	$\pm1\%$	$\pm1\%$	$< \pm1\%$
Missing transverse momentum	$< \pm1\%$	$< \pm1\%$	$\pm3\%$
PDF	$\pm4\%$	$\pm2\%$	$\pm5\%$
ISR/FSR	$\pm3\%$	$\pm5\%$	—
Cross section	8%	10%	24%

Systematics in CMS FCNC *tHq* search

Prior uncertainties, effects on event yields only (not impacts on limits)

Source of uncertainty	Magnitude (%)
Luminosity	2.6
PDF	10
$E_{\mathrm{T}}^{\mathrm{miss}}(> 50\ \mathrm{GeV})$ resolution correction	4
Jet energy scale	0.5
b-tag scale factor ($t\bar{t}$)	6
$e(\mu)$ ID/isolation (at $p_{\mathrm{T}} = 30$ GeV)	0.6 (0.2)
Trigger efficiency	5
$t\bar{t}$ misidentification	50
$t\bar{t}, WZ, ZZ$ cross sections	10, 15, 15
τ_{h} misidentification	30
Diphoton background	50

W helicities from asymmetries in ATLAS

- Utilise asymmetries

$$A_{\pm} = \frac{N(\cos\theta^* > z_{\mp}) - N(\cos\theta^* < z_{\mp})}{N(\cos\theta^* > z_{\mp}) + N(\cos\theta^* < z_{\mp})}, \quad z_{\mp} = \mp\left(\sqrt[3]{4} - 1\right)$$

  - They relate[1] to W-helicity fractions allowing to extract $F_{L,R,0}$ easily:

$$\begin{cases} A_+ = 3\beta\left(F_0 + (1+\beta)\,F_R\right), \quad \beta = \sqrt[3]{2} - 1, \\ A_- = 3\beta\left(F_0 + (1+\beta)\,F_L\right), \\ F_R + F_L + F_0 = 1 \end{cases}$$

  - Despite the simplicity, the asymmetries are quite sensitive to V_R, g_L, g_R couplings[1]

[1] Aguilar–Saavedra et al., Eur. Phys. J. C50 (2007) 519–533

Signal modelling in CMS W-helicity measurements

- In all CMS analyses signal is modelled by reweighting SM sample(s)
  - Probability density for a single decaying top quark:

$$\rho\left(\cos\theta^*; \mathbf{F}\right) = \frac{3}{8} F_L \left(1 - \cos\theta^*\right)^2 + \frac{3}{4} F_0 \sin^2\theta^* + \frac{3}{8} F_R \left(1 + \cos\theta^*\right)^2,$$

    where $\mathbf{F} \equiv \{F_L, F_0, F_R\}$ are the helicity fractions and $\cos\theta^*$ is calculated at the generator level
  - Event weight for a target configuration $\mathbf{F}$ is calculated as

$$w\left(\mathbf{F}\right) = \prod_i \frac{\rho\left(\cos\theta_i^*; \mathbf{F}\right)}{\rho\left(\cos\theta_i^*; \mathbf{F}_{\mathrm{SM}}\right)},$$

    where the product is taken over all top quarks in the event
  - (Two) components of $\mathbf{F}$ are used directly in the fit to reconstructed $\cos\theta^*$ as the parameters of interest
- In ATLAS, CDF, and DØ measurements the signal was modelled as a mixture of three templates
  - Correspond to F_L, F_0, or $F_R = 1$, the other two fractions are set to zero

Systematics in ATLAS W-helicity measurement

Source	Uncertainties		
	F_0	F_L	F_R
Signal and background modelling			
Generator choice	0.012	0.009	0.004
ISR/FSR	0.015	0.008	0.007
PDF	0.011	0.006	0.006
Top quark mass	0.016	0.009	0.008
Misidentified leptons	0.020	0.013	0.007
W+jets	0.016	0.008	0.008
Other backgrounds	0.006	0.003	0.003
Method-specific uncertainties	0.031	0.016	0.035
Detector modelling			
Lepton reconstruction	0.013	0.006	0.007
Jet energy scale	0.026	0.014	0.012
Jet reconstruction	0.012	0.005	0.007
b-tagging	0.007	0.003	0.004
Calorimeter readout	0.009	0.005	0.004
Luminosity and pileup	0.009	0.004	0.005
Total systematic uncertainty	0.06	0.03	0.04

CMS W-helicity measurement in $\ell +$ jets, 7 TeV

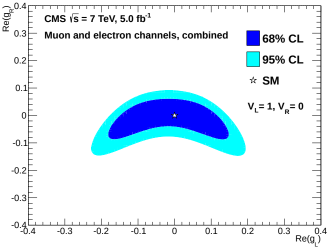
Systematic Uncertainties	μ+jets ($\cos\theta^*$) 3D fit $\pm\,\Delta F_0$	μ+jets ($\cos\theta^*$) 3D fit $\pm\,\Delta F_L$	μ+jets ($\cos\theta^*$) 2D fit $\pm\,\Delta F_0$	e+jets ($\cos\theta^*$) 3D fit $\pm\,\Delta F_0$	e+jets ($\cos\theta^*$) 3D fit $\pm\,\Delta F_L$	e+jets ($\cos\theta^*$) 2D fit $\pm\,\Delta F_0$	ℓ+jets ($\cos\theta^*$) 3D fit $\pm\,\Delta F_0$	ℓ+jets ($\cos\theta^*$) 3D fit $\pm\,\Delta F_L$	ℓ+jets ($\cos\theta^*$) 2D fit $\pm\,\Delta F_0$
JES	0.005	0.003	0.001	0.006	0.002	0.003	0.006	0.003	0.001
JER	0.009	0.005	0.001	0.014	0.009	0.003	0.011	0.007	0.001
Lepton eff.	0.001	0.001	0.001	0.009	0.012	0.015	0.001	0.002	0.002
b-tag eff.	0.001	0.001	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	0.001	0.001	$< 10^{-3}$	$< 10^{-3}$
Pileup	0.013	0.011	0.008	0.008	0.007	0.005	0.002	$< 10^{-3}$	0.008
Single-t bkg.	0.004	$< 10^{-3}$	0.003	0.004	$< 10^{-3}$	0.004	0.004	0.001	0.003
W+jets bkg.	0.019	0.007	0.006	0.009	0.006	0.022	0.013	0.004	0.006
DY+jets bkg.	0.002	0.001	0.001	0.001	$< 10^{-3}$	0.001	0.001	$< 10^{-3}$	0.001
MC statistics	0.016	0.012	0.009	0.019	0.015	0.012	0.016	0.012	0.010
Top-quark mass	0.011	0.008	0.007	0.025	0.018	0.014	0.016	0.011	0.019
$t\bar{t}$ scales	0.013	0.009	0.007	0.015	0.018	0.030	0.009	0.009	0.011
$t\bar{t}$ match. scale	0.004	0.001	0.006	0.010	0.013	0.016	0.011	0.010	0.008
PDF	0.002	0.001	0.003	0.004	0.002	0.002	0.002	$< 10^{-3}$	0.003

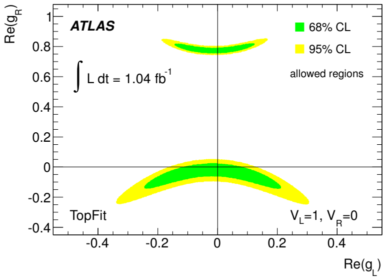
CMS W-helicity measurement in $\ell +$ jets, 7 TeV

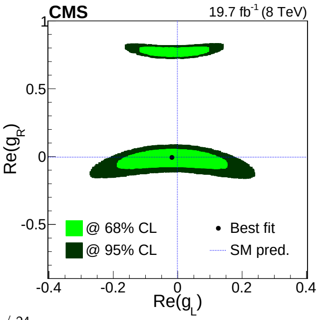
Leptonic branch: $\cos\theta^*$					
Fit	Channel	$F_0 \pm$ (stat.) $\pm$ (syst.)	$F_L \pm$ (stat.) $\pm$ (syst.)	$F_R \pm$ (stat.) $\pm$ (syst.)	ρ_{0L}^{stat}
3D	μ+jets	0.674 ±0.039±0.035	0.314 ±0.028±0.022	0.012 ±0.016±0.020	−0.95
3D	e+jets	0.688 ±0.045±0.042	0.310 ±0.033±0.037	0.002 ±0.017±0.023	−0.95
2D	μ+jets	0.698 ±0.021±0.019	0.302 ±0.021±0.019	fixed at 0	−1
2D	e+jets	0.691 ±0.025±0.047	0.309 ±0.025±0.047	fixed at 0	−1
Hadronic branch: $\lvert\cos^{\text{had}}\theta^*\rvert$					
Fit	Channel	$F_0 \pm$ (stat.) $\pm$ (syst.)	$F_L \pm$ (stat.) $\pm$ (syst.)	$F_R \pm$ (stat.) $\pm$ (syst.)	ρ_{0L}
2D	μ+jets	0.651 ±0.060±0.084	0.349 ±0.060±0.084	fixed at 0	−1
2D	e+jets	0.629 ±0.060±0.093	0.371 ±0.060±0.093	fixed at 0	−1

Fit	Channel(s)	Branch	Fraction	± (stat.) ± (syst.) [total]	ρ_{0L}^{total}
3D	ℓ+jets	l	F_0	0.682 ±0.030±0.033 [0.045]	−0.95
			F_L	0.310 ±0.022±0.022 [0.032]	
			F_R	0.008 ±0.012±0.014 [0.018]	
2D	μ+jets	l+h	F_0	0.694 ±0.020±0.025 [0.032]	
			F_L	0.306 ±0.020±0.025 [0.032]	−1
2D	e+jets	l+h	F_0	0.674 ±0.025±0.028 [0.037]	
			F_L	0.326 ±0.025±0.028 [0.037]	−1
2D	ℓ+jets	l+h	F_0	0.685 ±0.017±0.021 [0.027]	
			F_L	0.315 ±0.017±0.021 [0.027]	−1

Limits on anomalous *Wtb* couplings

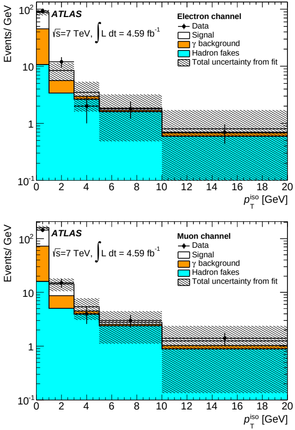






$t\bar{t}\gamma$

- ATLAS measurement at 7 TeV[1]
  - $t\bar{t} \to \ell + \text{jets}$
  - Fiducial phase space
    - Photon: $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, $|\eta| < 2.37$
    - Leptons (e/μ): $p_{\mathrm{T}} > 25\,\mathrm{GeV}$, $|\eta| < 2.5$
    - Jets: $p_{\mathrm{T}} > 25\,\mathrm{GeV}$, $|\eta| < 2.5$
  - Fit photon track-isolation p_{T}
    - $\sum p_{\mathrm{T}}$ of tracks within $\Delta R < 0.2$
    - Data-driven templates for prompt photons and fakes
  - Results:
    - Observation of $t\bar{t}\gamma$: $5.3\,\sigma$
    - $\sigma_{\text{fid}} = 76 \pm 8\,(\text{stat.})\,^{+17}_{-13}\,(\text{syst.})\,\pm 1\,(\text{lumi.})\,\text{fb}$
      theory prediction: $48 \pm 10\,\text{fb}$



- CMS measurement at 8 TeV[2]
  - Select $t\bar{t} \to \mu + \text{jets}$ events. Fit to photon charged-hadron isolation
  - $R \equiv \sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}} = \left(1.07 \pm 0.07\,(\text{stat.})\,\pm 0.27\,(\text{syst.})\right) \cdot 10^{-2}$

[1] arXiv:1502.00586, submitted to Phys. Rev. D [2] TOP-13-011